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STATE OF THE ART AND PROSPECTS FOR DEVELOPING CALCULATION METHODS AND EXPERIMENTAL INVESTIGATIONS OF RADIATIVE HEAT TRANSFER AND FOR PRACTICAL APPLICATION OF THEIR RESULTS

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This article gives an overview of domestic theoretical and experimental investigations of radiative and combined heat transfer performed in recent years and formulates prospective lines of their development.

Among scientific problems in the field of heat and mass transfer, issues of radiative and combined heat transfer occupy a very important place. Problems of heat transfer by radiation are encountered in very different branches of the national economy. In connection with a general tendency of development of industry and technology toward intensifying technological processes and utilizing new high-temperature power technologies the role of heat transfer by radiation will grow in every possible way. In a number of industries it is the major mode of energy transfer in technological processes.

For years, according to the scientific and technological assessment developed by the Scientific Council on the problem "Mass and Heat Transfer in Technological Processes" of the State Committee for Science and Technology of the USSR (1970), the USSR had occupied the leading position in the field of the theory and methods of calculating heat transfer by radiation. Soviet scientists developed the fundamental principles of radiative heat transfer (flow algebra, a method of balance, differential and zonal methods of calculation in various modifications, and so on) and performed extensive investigations in the field of integral equations of radiation transfer, solving a number of classical problems of radiative heat transfer, taking account of surface and volume scattering anisotropy, etc. The above scientific and technological assessment stated that by that time a classical theory of thermal radiation, conforming to the state of thermodynamic balance of radiation and matter, had been created.

The mathematical basis of the theory of radiative heat transfer is an integrodifferential equation of transfer formed for the radiation spectral intensity and an equation of boundary conditions to it, having an integral character. Both these equations are distinguished for their great mathematical complexity and are based as a rule on a series of physical premises: the medium is assumed to be in the state of local thermodynamic equilibrium, frequency scattering and the influence of radiation polarization are neglected, and all spectral radiative characteristics of the medium and the boundary surface are assumed known.

In the theory of heat transfer by radiation the indicated equations are used as the starting base for constructing differential, integral, and algebraic methods of calculation. All these calculated materials contain as a consequence the enumerated physical assumptions and are under development at present in connection with the needs brought forward by developing new fields of science and technology as well as by creating new technological processes and improving available ones.

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Therefore in recent years the creation of sufficiently general and reliable methods of calculation for radiative and combined heat transfer has been performed along the following lines:

a theory of radiative heat transfer based on more rigorous and exact kinetic equations of radiation transfer taking into account thermodynamic nonequilibrium of the emitting medium, radiation polarization, and frequency scattering;

theoretical methods of calculating heat transfer by radiation with allowance made for selectivity of radiation and absorption of various bodies and media, involved in heat transfer by radiation (gases, disperse media, liquids, and solids), and for anisotropy of volume and surface scattering in different directions and frequencies;

calculation methods for nonstationary processes of radiative heat transfer with allowance made for the finite radiation velocity in transient processes;

mathematical (analytical and numerical) methods of solving equations of radiative heat transfer;

zonal methods to calculate heat transfer by radiation with allowance made for nonuniformity of thermal, geometric, and optical characteristics throughout the zones, selectivity of radiation from media and bodies, and anisotropy of bulk and surface scattering in systems;

theoretical methods of investigating combined heat transfer under the internal problem, characteristic of numerous technical applications, taking into account special features of real working media and limiting surfaces;

mathematical methods to solve the equations describing the process of combined heat transfer in technological apparatuses;

obtaining experimental data required to develop calculation methods for radiative and combined heat transfer in the elements of various heat-exchange apparatuses.

The performed analysis of domestic investigations carried out in recent years makes it possible to point out the most important achievements in developing methods of radiative and combined heat transfer and the practical application of their results and also to draw certain conclusions in terms of comparison with the world level and the prospects of their further development.

Among the major outcomes of development of radiation transfer theory which characterize its current state of the art are:

constructing and investigating a generalized classification of the basic characteristics of hemispherical and volume radiation in systems filled with a selectively emitting and absorbing medium which is anisotropically scattering and is limited by reflecting and emitting surfaces;

deriving on the basis of the indicated classification the systems of generalized integral equations describing the generalized statement of the problem which covers all the eight basic types of the problem's statement, having a unique solution;

the development of new methods of solving integral equations of radiation transfer related to the theorem of transformation or the duality principle, one aspect of which implies that the solution of one statement of the problem can be transformed to another, its dual;

obtaining a ramified system of closure equations for all basic statements of the problem and reciprocity equations containing resolvents and resolving angular coefficients of radiation taking into account multiple reflections on the boundary of the system and multiple scatterings throughout the volume of the medium;

the development and application of three basic forms of representation of generalized zonal and iteration zonal methods for calculating radiative heat transfer;

constructing the foundations of a stochastic theory of radiation transfer resting on the law of probability conservation;

the introduction of the probability characteristics of radiation transfer based on the closure equations of the system expressing the law of probability conservation, which makes it possible to determine not only geometric probabilities but also more general optical geometric probabilities of radiation transfer in the system filled with the absorbing and anisotropically scattering medium;

introducing the entropy characteristics of nonequilibrium radiating systems, constructing the classification of physical entropy characteristics of hemispherical and volume radiation, introducing the notions of spherical and hemispherical vectors of radiation entropy as well as constructing integral equations for the physical radiation entropy densities.

In obtaining the enumerated results much of the credit must go to Professor Yu. A. Surinov and his disciples [1, 2].

Solving the problems of radiant heat transfer in closed systems is considered in the investigations of the Dnepropetrovsk Metallurgical Institute [3], the Moscow Technological Institute of the Food Industry [4] and others. A software complex on the calculation of radiative heat transfer coefficients in multiply connected axisymmetric systems filled with an emitting and absorbing medium is developed at the Urals Polytechnic Institute [5]. The calculated scheme of the software package is based on the parallel-plane method.

A software complex of calculating radiation transfer in axisymmetric volumes developed in the Kazan Aviation Institute [6] serves to determine the radiation characteristics in homogeneous and two-phase media. Radiation energy transfer is described by the Boltzmann kinetic equation. A spherical harmonics method is chosen as the basic method for solving the equations of radiation transfer. The software complex is used to solve a number of technical (calculation of distribution of radiation heat fluxes in power plants) and scientific problems (determining electrooptical properties of the condensed phase, concentration and disperse composition of condensed particles, temperature distribution in the medium).

Impressive progress is observed in the investigations of combined (radiative convective and radiative conductive) heat transfer in absorbing, emitting, and scattering media.

At the Institute for High Temperatures of the Russian Academy of Sciences and at the Institute of Physicotechnical Problems of Power Engineering of the Academy of Sciences of Lithuania important results are obtained on the development of mathematical modeling and numerical methods of calculation for radiation fluxes in intricately shaped channels filled with a nonisothermal high-temperature medium [7, 8]. These investigations take account of the main factors governing the intensity of radiative heat transfer: temperature and concentration nonuniformities of the emitting, absorbing, and scattering medium, an intricate shape of the channel cross section, selectivity of molecular gases, scattering by particles of various sizes, and the nonblackness of the channel walls.

A two-dimensional calculation of mixing and transfer of radiation in the wall cooling curtains in combustion chambers of hydrocarbon fuels has shown that placing even optically transparent curtains considerably decreases radiant fluxes of heat into the walls as a result of mixing of combustion products with the curtains and the corresponding decrease in the temperature of the wall emitting layer [9].

An extensive complex of experimental theoretical investigations of radiative-convective heat transfer in interaction of high temperature flows with bodies has been performed [10, 11].

It can be stated on the whole that the basic problems of further development of theoretical investigations into radiative-convective heat transfer are by now in:

taking account of radiation selectivity including anisotropy of volume and surface scattering and the influence of gasdynamic factors on the processes of combined heat transfer;

the development of numerical methods for calculating the heat flux and its divergence consistent with the gasdynamic computational grid;

developing numerical methods to solve differential equations of transfer, containing powerful source terms, and developing effective algorithms for combustion problems;

taking account of turbulent pulsations of the flow in connection with the necessity of time-averaging quantities which are related in a nonlinear manner to the temperature and with the occurring interference of radiation with the flow turbulent structure;

the choice of the boundary conditions for radiation intensity in connection with the need to take into account the semitransparency or volume radiation of surfaces limiting the system;

creating automated systems to solve various heat-engineering problems including integration of large software packages;

the simplification of the problems of combined heat transfer through the use of the possibilities which are provided by applying the principles of similarity theory.

Naturally, there also exist many other problems which are mainly associated with the solution of various special problems in one or another field of application.

No less important an issue of mathematical modeling remain the problems of radiative-conductive heat transfer arising due to the necessity of taking into account semitransparency and volume radiation and complicated by determination of the boundary conditions both on the surface and deep in the semitransparent layer, for example, with phase transitions in it. A survey of advances in this field of research is most completely given in [12-14].

Studying the problems of radiative-conductive heat transfer is further developed in scientific centers which have traditionally performed investigations into this field (the Institute for High Temperatures of the Russian Academy of Sciences, the Institute of Thermal Physics of the Siberian Branch of the Russian Academy of Sciences, the Institute of Physicotechnical Problems of Power Engineering of the Academy of Sciences of Lithuania, the Moscow Institute of Railway Transport Engineers, the Moscow Engineering Physics Institute, the Kiev Polytechnic Institute, and others). The fact of presenting more than 20 papers on this subject at the VIth All-Union Conference on Radiative Heat Transfer in Engineering and Technology (Kaunas, 1987) suggests a wide spread of investigations in this direction and their topicality.

Nevertheless to the present day the problem of mathematical modeling of radiative-conductive heat transfer in multilayer media of intricate geometry, especially in a multidimensional statement of the problem, is noted for considerable mathematical difficulty; its solution is limited by the potentials of a computer. The problem is made more difficult by substantial selectivity of the optical properties of these materials and the lack of data on their dependence on the temperature, phase state, service life, and operating conditions; therefore we simplify the problem when solving it. This also causes a search for approximate methods of solving the problem which are based on a separate determination of conductive and radiative constituents of combined heat transfer [15, 16]. The development of results of these investigations performed for stationary radiative-conductive heat transfer [17] made it possible to obtain generalizing dependences to determine heat fluxes and temperature fields of semitransparent materials under substantial nonstationarity as linear functions of one decisive criterion [18].

The work [19] is devoted to general approaches to methods of investigation and solving the problems of radiative-conductive heat transfer theory. It proposes a method based on using zonal approximations of the surface density of resultant radiation and the volume resultant radiation density and on applying the method of successive two-sided approximations to the solution of the obtained approximate boundary problems. The presented approach makes it possible to obtain the temperature field of the system as a limit of nondecreasing and nonincreasing sequences of approximate solutions of the problems in question which uniformly converge on every specified time interval. A numerical solution of the nonstationary problem of radiative-conductive heat transfer in a system of two coaxial cylinders of finite length separated by a diathermal medium is given as an example.

The methodology of using the diffusion approximation to calculate radiative-conductive heat transfer in materials like porous oxide ceramics, plasma-sprayed coatings, and light-weight fibrous thermal insulation is successfully developed by a team of researchers supervised by V. A. Petrov [20, 21]. The complex approach consists, on the one hand, in developing on the basis of this approximation mathematical models of radiative-conductive heat transfer with different initial and boundary conditions and on the other hand, in developing methods of solution for inverse problems of radiative and radiative-conductive heat transfer with the aim to determine the optical properties (the absorption factor, the radiation diffusion coefficient, and the refraction index) and the thermal conductivity. In an effort to check the correctness of the created physical and mathematical model of radiative-conductive heat transfer describing heating of ceramics by intense radiation fluxes and the validity of calculated data obtained with it, experiments on heating ceramics by radiation of varying spectral composition have been performed.

Rigid requirements for stability of functional characteristics and great sophistication and high costs of large-scale space constructions (orbital stations, platforms, antennas, solar concentrators, aeroassisted orbital transfer spacecraft, etc.) make performing detailed investigations of radiative-conductive heat transfer urgent. Algorithms of solution of these problems are based on applying the finite-difference and finite-element method together with the zonal method. To solve an equation of radiation transfer in partially transparent scattering materials, the method of moments is used. Nonstationary inverse problems of radiative-conductive heat transfer have an extremal statement and are solved using the iteration regularization method [22]. The proposed methods of parametric identification [23, 24] extend the capabilities of the available experimental plants and stands and increase their capacity and accuracy, requiring no cardinal alteration of the equipment.

The most difficult stage of the numerical solution for a stationary problem of radiative-conductive heat transfer, determining the accuracy of the obtained results and the duration of the computational process, is calculating the radiative constituent of thermal balance for an element of a semitransparent medium. When analyzing heat transfer in multidimensional regions one most often uses zonal methods to calculate radiative energy transfer, which are distinguished for the complexity of the algorithm for computing optico-geometric coefficients, characterizing the radiation interaction of the surface and volume zones. The advantages of these methods can only be admitted in the special case when the optical properties of the semitransparent medium do not depend on temperature and we need not recalculate the optico-geometric coefficients on each iteration step.

Updating computer technology made it possible to approach the calculation of radiative energy transfer without any tentative assumptions if in the energy equation the influence of radiative transfer on formation of a temperature field is considered as the influence of the source. In the works of the Moscow Institute of Railway Transport Engineers it is proposed to compute the source by integrating the radiation intensity over the sphere at the point of the coordinate grid at which the source is located. The given method for calculing the characteristics of the radiation field was applied for the finite cylinder and plate with mirror, transparent, and opaque boundary surfaces.

A number of works deal with taking into account the optical characteristics of the boundary surfaces. The influence of diffusely reflecting and diffusely emitting boundaries on radiative heat transfer is studied in the Physicotechnical Institute of the Russian Academy of Sciences through the introduction of effective radiation temperatures. The obtained asymptotic solution for the problem of radiative heat transfer makes it possible to find the distribution of the temperature and the heat flux and to analyze the influence of emissivity factors on these quantities.

Investigations, interesting from the viewpoint of practical applications, of nonmonotonic temperature in radiative-conductive heat transfer in a two-layer system of practically transparent material on the boundary between the layers caused by diffuse reflection and heat release of a phase transition on the interior boundary are performed in the Kiev Polytechnic Institute [25].

It is noteworthy, however, that one may only arbitrarily refer these investigations to the theory of radiation transfer since the greater part of the works on radiative and combined heat transfer, in which there are substantial elements of the theory's development, is performed purposefully in the interest of numerous technical applications.

As was mentioned above, under modern conditions radiative heat transfer in technological processes is growing in importance. The role of radiation is particularly important in boiler unit furnaces, in metallurgical and other industrial furnaces, in electric furnaces and heat-treating furnaces of engineering industries, in combustion chambers of engines and gas-turbine plants, in tube furnaces of the petroleum and chemical industry, and in other units. The thermal regime of spacecraft is entirely governed by the conditions of heat transfer by radiation. The principle of recording of thermal radiation operates for many physical instruments and highly efficient measuring instruments and devices for control and automation of various technological processes.

Present-day advances in the field of investigation of combustion processes, heat transfer, and aerodynamics of furnaces (power-generating boilers, in particular) naturally open up new possibilities of improving calculation methods; however, unfortunately, they fail to ensure the prospect of creating a unified calculation method as yet which takes into complete account the basic features of the processes and correlates with the available experimental data well.

Increasing reliability and operation efficiency of a power-generating boiler furnace and the possibilities to promptly affect the generation of nitrogen oxides in the furnace are closely connected with optimization of the combustion process under real operating conditions of the unit with time-varying characteristics of the burned up fuel and other regime parameters of the furnace operation. Under the most severe conditions are the heating surfaces in the furnace which are subject to a high-temperature gas flow and corrosive and mechanical wear. Depending on the conditions of fuel and air supply the position of the flame in the furnace volume varies, resulting in heat (across flows) and temperature stratifications which impair reliability and technical-and-economic indexes of operation of the equipment. In this connection on-line control of the conditions of the furnace process within the system of expert technical furnace diagnostics is the most important way to improve reliability of its operation and to solve the major problems of power and resource saving in heat power engineering.

The influence on the combustion and heat transfer processes of many different factors including peculiarities of the furnace aerodynamics is taken into account by a mathematical model of the furnace used as a basis of the diagnostic system and based on equations of energy and material balance for volume and surface zones of the furnace [26, 27].

Diagnostic software of the system incorporates a series of analyzed indexes of the furnace operation, their estimation methods, evidence of the presence of defects and their localization, normal operation conditions, and corresponding algorithms and programs. On-line control of reliability indexes is executed in the most stressed zones of the furnace by measuring local values of the incident and absorbed radiation flow densities and the temperature of metal of the waterwall tube wall.

Expert technical furnace diagnostics is presently utilized on a BKZ-420-PT2 liquid-bath steam boiler at the Ust'-Ilimsk heat and electric power plant. In realizing technical diagnostics systems there emerges a problem of correct diagnosis of the situation on the basis of the available partial models, for example, those of thermal work of the furnace and steam superheating and tail heating surfaces which, in its turn, gives rise to the problem of joining in the unit's mathematical model both mathematical models of the processes proper and an empirical knowledge of the unit's performance obtained as a result of tests and its operating experience. The approach in question clearly impairs the versatility of the technical diagnostics system, yet makes it possible to create the system most adapted to the object and to take into account the real operating level of the boiler at this station.

Insufficient operating reliability of powerful steam boilers which accounts for 70% of failures in the power unit operation is connected with damage to furnace waterwalls caused primarily by the fact that operating and maintenance personnel are not timely informed of their operating conditions in the context of reliability and wear of the technical resource.

Based on analysis of the character and statistics of damage to the furnace waterwall tubes of a TGMP-204 gas-dense boiler of a 800 MW unit the Kiev Polytechnic Institute has developed [30] a mathematical model taking into account the tube thermostressed state both from stationary loads, one-sided heating, nonuniform distribution of the heat flux along the furnace height and across its width, etc. and from varying loads in transient regimes (the internal pressure fluctuations with starts-stops, varying loads, the absorbed heat flux and working body temperature pulsations). Besides, account is taken of the variation in the boundary conditions on the waterwall tube inner surface due to the growth of thermal resistance of interior deposits and the variation in its geometric dimensions under the action of corrosive processes on the inner and outer tube surfaces.

The general issue of mathematical modeling of radiative heat transfer in steam generator furnaces is reflected in V. N. Andrianov's works [31]. Spectral transfer equations and boundary conditions are used as a starting base of the net method. The developed program of numerical calculation made it possible to find the fields of radiative and energy characteristics. Radiative properties were prescribed in selective and gray variants and the furnace medium was assumed emitting, absorbing, and anisotropically scattering. To allow for the real optical characteristics for combustion products of coals from differents beds, special subprograms are developed in which the Mie theory (for dispersed components) and data of NASA (for radiating gases) have been used.

The obtained results of the calculation have shown a substantial nonuniformity in the distribution of energy characteristics in the furnace, which is of great practical importance and permits calculations of heat transfer on a more accurate and rigorous base. The comparative analysis of the results has shown that in calculating heat transfer by radiation one can use an idealized model of the furnace medium (a gray one with the averaged "forward-back" indicatrix) and then correct with pre-found correction functions values that turn out to be small.

Methods of investigating and calculating radiative characteristics of furnace media and their influence on radiative heat transfer, in particular, on such an important heat engineering parameter as the thermal efficiency coefficient of heat absorbing surfaces are presently developed at the I. I. Polzunov Central Boiler and Turbine Institute, the Institute of Power Engineering, the All-Union Heat Engineering Institute, the Krasnoyarsk Institute of Non-Ferrous Metals, the Academic Scientific Complex "A. V. Luikov Institute of Heat and Mass Transfer of the

Academy of Sciences of Belarus," the Institute for High Temperatures of the Russian Academy of Sciences, and the Ural Polytechnic Institute. Theoretical investigations and experimental measurements of integral [32-34] and spectral [35, 36] values of this parameter have been performed with allowance for the character of the temperature fields as applied to boiler unit furnaces.

Making good use of solid fuel is substantially complicated by reduction in the quality of coals supplied to electric stations. The complex solution is troublesome since it is necessary to link contradictory problems: to intensify the processes of combustion and heat transfer by increasing the temperature level and to decrease generation of toxic discharge by reducing the temperature in the combustion zone. The analysis of these directions shows that the most promising are low-temperature methods of burning which are realized in circulating or stationary fluidized-bed furnaces and in swirling-type low-temperature LPI furnaces.

Common for the above furnaces or their combinations is the reduction in the temperature level in the combustion zone at the expense of an increase in the fuel particle size and transfer of the fuel burn-out from the limited zone near burners to most of the furnace volume. The increase in the burn-out time for large particles at low temperatures as compared to high-temperature burning of coal dust is compensated by increased time of stay in the furnace due to multiple circulation. Investigations of optimizing heat transfer with low- temperature methods of burning are carried out at the Central Boiler and Turbine Institute [37], St. Petersburg State Technical University [38], the All-Union Scientific Research Institute Énergotsvetmet [39], the Academic Scientific Complex "A. V. Luikov Institute of Heat and Mass Transfer of the Academy of Sciences of Belarus" [40], and others.

Special interest has grown in the issues of environmental safety of existing industries and in accordance with this, particularly, in the problems of creating power-technological equipment meeting these requirements. At the VIIth All-Union Conference on Radiative Heat Transfer (Tashkent, 1991) a great body of results of interesting investigations (for example, [41-45] and others) concerning ecological aspects in the processes of combustion and heat transfer in burning organic fuels were presented. Nevertheless it is pointed out in the resolution of the conference that these issues receive insufficient attention as yet.

In recent years considerable progress has been made in modeling and methods of calculation for radiative heat transfer and energy transfer by radiation in substantially inhomogeneous gases and high-temperature volumes containing solid particles under conditions of the selective character of radiation and absorption (both in the working volume and on its limiting surfaces) allowing for the influence of scattering and the three-dimensional character of radiation transfer.

These advances were stimulated by the development and optimization of the processes of burning organic fuels (gas, liquid, or solid) in power engineering and metallurgy heat engineering, where the objects of calculation are steam generators of large thermal power stations, furnaces, diversified furnaces for heat treatment, devices for radiative gas heating, etc., and by creating high-temperature power units (combustion chambers and flue gas paths in rocket and gas-turbine engines, channels of magnetohydrodynamic generators, etc.). The basic results of investigations and developments on radiative heat transfer in these fields are generalized in a series of monographs, reference publications [13, 46-52], and original publications of recent years [53-55].

Modeling of combined radiative-convective and radiative-conductive heat transfer was substantially developed under conditions of considerable flow inhomogeneities, governing the complex character of the problems, and the selective character of radiation, absorption, and scattering. These problems are essentially related to the development of high-temperature technology (high-power technological plasmatrons, continuous lasers, magnetohydrodynamic generators, solid-propellant rocket engines, thermal protection of reusable apparatuses, etc.).

Basic features of the conditions under which radiative and combined heat transfer takes place in the indicated technical devices and which govern the complex character of the heat transfer problems are as follows:

a substantially two- or three-dimensional character of radiation transfer determined by the intricate internal geometry and the comparability of governing dimensions in different directions of working volumes;

substantial inhomogeneity of temperature fields and concentration patterns of emitting components and solid (slag and soot) particles determined by both fuel burn-out or vapor condensation and the gasdynamics of the flow (formation of boundary layers, jet and separation zones, intricacies of the flowing portion geometry);

a selective character of radiation and absorption of the gas volume and materials and of the limiting surfaces which stems from high temperatures and the presence of various additives (for example, ionizable additives in MHD-generators) characterized by a pronounced spectral character of radiation, deposits on the surfaces, as well as by scattering anisotropy on particles;

a conjugate character of radiative and combined heat transfer caused either by substantial nonstationarity of the processes (as, for example, in rocket engines or in channels of solid-fuel MHD-generators) or by considerable inhomogeneities of the working-volume wall surfaces.

Accumulated experience in solving the problems of radiative and combined high-temperature heat transfer shows that further development of modeling of radiative transfer and related processes under diverse conditions of the developed theories and technical devices should go hand in hand with creating computer systems of automated calculation for radiative heat transfer. Such various-purpose systems (from fairly general systems where radiative properties of various media and materials are involved to narrow-purpose systems for specific classes of problems) enable one not only to generalize the available information on properties, methods of integrating radiation-transfer equations, and statements and methods of solution for specific problems but also to systematize subsequent investigations undertaken to obtain deficient information. Such computer systems for automated solution of radiative heat transfer problems may have different sophistication levels and their corresponding scientific data banks.

The following systems and data banks may be considered as an example.

1. Physical and mathematical models of optical properties of homogeneous substances in technically important temperature intervals.

2. Models of the observed optical properties of technically important gas and gas-disperse mixtures.

Developments of automated banks of dataon radiative characteristics of substances and the necessary primary spectral information and data on spectral and group models of effective optical characteristics for technically important objects (for example, on models of narrow and wide bands, on emissivities and absorptivities) are to be connected with both indicated leads of work.

The following level of computer systems may be connected with these leads of work.

3. Creating a bank of computational models of radiative transfer (methods to integrate a radiation-transfer equation) in volumes of varying geometry with allowance for the specific properties of radiation transfer (temperature and concentration nonuniformity, scattering, etc.).

This level of computer systems should be connected with the first two levels since the methods of integrating the radiation-transfer equation are to be in agreement with the models of optical properties.

4. Problem-oriented system programming for solving specific classes and types of problems of radiative and combined heat transfer (for example, specific kinds of technical devices or certain types of geometric objects).

Such a program of creating computer systems of different levels of sophistication and purpose helps join the specialists' efforts, perform coordinated investigations, and produce practice-oriented computer systems which are also of undeniable commercial interest. Allowing for the actually existing situation in the field of modeling and calculations of radiative and combined heat transfer, it seems appropriate to start implementing a similar program with the class of problems related to radiative heat transfer in processes and devices for burning of organic fuels by using the currently available experience in constructing similar computer systems [56, 57].

The most significant work on developing methods of mathematical modeling and calculation for radiative and combined heat transfer in furnaces and high-temperature metallurgical units is under way in the Ural Polytechnic Institute [49, 58], the Moscow Institute of Steel and Alloys [59], the VNIIMT [60], VNIIEnergotsvetmet [61, 62], the Dnepropetrovsk Metallurgical Institute [63], the Institute of Gas of the Academy of Sciences of the Ukraine [64], and others. Media which are dealt with in metallurgy often have temperature-dependent properties. They are thermally massive bodies for which not only the statistics but also the dynamics of processes is important. They are usually high- temperature processes in which it is necessary to take account of all modes of heat transfer, i.e., processes of combined heat transfer. These processes are further complicated by the intricate geometry of the units' working volume and the structure of the treated materials.

Therefore, in the modern stage, achieving the objectives of strategic and tactical control of heat engineering processes under the given conditions can be realized to the greatest extent with the combined use of the so-called complete models (of the top level) and simplified models (of the second and the third levels) [49]. Naturally, such a classification of models is fairly conventional; it is somewhat related to the modern level of development of the mathematical modeling methods and computer engineering tools. When applied to heat engineering units, as practice shows, the complete models are to contain the heat-balance and heat conduction equations in the complex statement and equations of motion and physicochemical reaction. The simplified middle-level models commonly contain the two-dimensional or even one-dimensional statement and simplified geometry; differential equations are often brought to the linear statement. Finally, the third-level models are, for example, various polynomial models, linear dynamic models with fixed parameters, etc. The existing computer park corresponds to a certain extent to this classification. At present the possibility to take into account the basic features of the real technological process with the estimation (to sufficient accuracy) of integral and local characteristics of combined heat transfer in the real situation of the working process is involved in the notion of the complete model for calculating processes of radiative and combined heat transfer.

As experience in carrying out research and development work shows, in the modern stage the solution algorithm for the energy-transfer equation in the zonal statement, when a transition from complicated integrodifferential equations to algebraic ones is realized in a form accessible for a numerical solution, complies with the requirements of a sufficiently accurate model of the processes of combined heat transfer as applied to metallurgical units. At the same time the level of detail of the solution may be fairly high, the number of elements (equations) being very large, which ensures the necessary accuracy and acceptable calculation time on modern computers.

A series of forms for writing the applied systems of multizonal equations is presently known, including H. Hottel's system, which has gained worldwide acceptance, and also the systems of A. E. Klekl' and V. G. Lisienko [58] with the introduction of selective coefficients of radiative transfer. However, for technological purposes, in particular, for metallurgical processes when as has been noted there are two or several thermally massive viscous media involved in the process of heat and mass transfer and the value of not only integral but also local characteristics is required, using these equations turns out to be insufficient. In this case the zonal equations of heat balance and heat transfer are supplemented with those of motion and heat conduction. With such a statement there emerges a complex of problems in algorithmizing and solving the systems of equations, whose solution has led to the creation of a new dynamic (conjugate) zonal-nodal method. Thus, application of fundamental tenets of transfer theory enables one to work out unified methodological approaches in constructing determined models of control for both technological processes and production. Applying complete and simplified models of control provides the possibility to reveal specific conditions of the optimal production technological and structural factors: the optimum of the flame length, the heat transfer efficiency-regeneration degree relation in synchronous intensification, the relation between fuel consumption and capital outlays, etc.

Industrial furnaces are one of the major types of heat-consuming equipment in ferrous and nonferrous metallurgy, engineering industry, and other branches of the national economy. The possibility to substantially increase the capacity of industrial furnaces and widespread adoption of energy-saving technological processes go hand in hand with creating new progressive devices for heat recuperation whose application permits a 20-30% reduction in fuel consumption.

At VNIPITeploproekt the methods for calculating radiative heat transfer are developed and various recuperator constructions are adopted; voluminous practical material has been accumulated which makes it possible to efficiently choose recuperators according to specific operating conditions of furnaces: heating, heat-treating, and melting ones.

Developed on an extensive scale have been resources-saving, environmentally safe autogenous technologies of processing sulfide raw material of heavy nonferrous metals. Autogenous processes of flare and flash smelting and those of bubble liquid-bath smelting have gained industrial use. An efficient combined process of flare-bubble smelting is under development. Further improvement of these technologies is connected with the creation of new highly efficient units based on scientifically substantiated methods of thermal calculation. However, the theory of thermal work of these units remains insufficiently developed. Fundamental principles of their calculations and design are not developed because of the wide variety of units. This has predetermined the use of simplified calculation methods for autogenous processes reduced basically to drawing up material and heat balances. The activities of the

State Institute of Nonferrous Metals, the All-Union Scientific Research Institute of Power Engineering and Metallurgy of Nonferrous Metals, the Moscow Institute of Steel and Alloys, the Krasnoyarsk Institute of Nonferrous Metals, etc. [66-72] are recently devoted to theoretical problems of combined heat transfer. In particular, work carried out by the Krasnoyarsk Institute of Nonferrous Metals seeks to improve the calculation method and to investigate and optimize thermal regimes and construction of the elements in power technological complexes of autogenous smelting. As a result, calculated models of the heat-transfer processes in oxygen-flare and flash smelting furnaces, in the superlayer space of Vanyukov's furnaces, and in the complex Vanyukov's furnace-boiler-utilizer are created and have found practical application [68, 69]. The zonal method of calculation is used as a base of three-dimensional mathematical models. The models take account of special features of the elements and their layout in the complex, patterns of development and burnout of the flare, specific features of motion of weld products, the presence of the skull layer on limiting surfaces, different cooling systems for the lining, mass transfer with a bubbled melt bath, and radiation selectivity and scattering. The models are used for the analysis of heat transfer in variously designed flare-bubble complexes [70, 72]. As a result, for the first time detailed indexes of the units' thermal work have been obtained, the influence of the regime and design parameters on heat transfer has been analyzed, practical recommendations for operating and developed designs have been worked out, and an engineering method for calculating heat transfer in furnaces and autogenous smelting complexes is under development.

Mathematical models and software packages for calculating combined heat transfer enabling one to determine to acceptable accuracy temperature and resultant heat flux fields in combustion chambers as applied to tube furnaces and flare plants of the gas, petrochemical, and petroleum industry are presented in [73-75]. The procedure developed on the basis of a zonal method [73] differentiates volume and surface zones in the working space whose geometric and optical type is prescribed by a special classifier. This makes it possible to determine the specific heat fluxes along the perimeter of a separate product coil tube and to calculate profiles of the resultant fluxes in separate points of waterwall tubes.

The work [74] describes a differential method for the calculation of external heat transfer in box-type tube furnaces based on a simultaneous numerical solution of the system of two-dimensional integrodifferential equations of radiative gasdynamics which is closed by equations of the (k-ε) model of turbulence and of a one-step exothermal model of fuel combustion. Radiation transfer in the absorbing, emitting, and scattering furnace medium is solved in the S_2-approximation of a discrete-ordinate method. The emission spectrum of combustion products is described by a six-band model taking into account the basic emission bands of H_2O, CO_2 and of soot.

Technological features of the objects of production and processing of gas and liquid fuels provide for their partial burning in flare plants by an open method. Safe operation of the equipment in the radiation zone and reliable protection of personnel call for a scientifically substantiated method to determine the parameters of the flame plants and their relative position on the basis of analysis of predicted thermal loads. For this purpose a mathematical model and programs for calculating the incident heat fluxes and the ground surface temperature in the zone of open gas flames are created [75]. The calculation procedure involves a mathematical model of heat and mass transfer and combustion in the flame and a calculation of heat transfer on the ground surface.

Software to fit a CAD system for the objects of production and processing of gas has been developed for the presented procedure. Calculations are realized on a personal computer of the PC family. For the convenience of users the results are presented graphically.

Based of investigations of radiative heat transfer, the optimization problems of increasing capacity of tunnel kilns, improving their operation stability and the quality of the manufactured products are solved. The zonal mathematical model and efficient computational algorithms form the basis for the calculation of radiative heat transfer in this case [76].

In glass furnaces, radiative heat transfer is also the major mode of heat transmission. The heat transfer system in them incorporates five surface zones (flame, the upper and lower charges, the working space masonry, and the basin) and two volume zones (furnace gases and a melt). The solution to the problem of heat transfer is found [77] with a zonal method using H. Hottel's procedure and enables one to determine the temperatures of all zones involved in the heat transfer and the flows of resultant radiation for each zone. On this basis a method of the heat-engineering calculation of continuous melting furnace baths is developed.

In food heat technology, new trends in industrial use of electromagnetic radiation energy of the infrared wave band for the purpose of intensifying various hygrothermal processes are successfully developed. Applying IR-radiation in the processes of drying, heating, hygro- and hydrothermal treatment of materials makes it possible to substantially intensify internal heat and mass transfer in capillary-porous colloidal and dispersed materials.

Generalization of results of investigating radiative heat transfer and energy transfer in these materials permitted the conclusion of the need for a complex consideration of various effects, their superposition and interference with the transfer processes: selectivity of absorption and multiple scattering in the object, a variation in the spectral composition of radiation in the process of propagation, molar and molecular moisture transfer, phase transitions, effects on the material structure and biochemical variations, superposition on radiation transfer of heat and moisture transfers in the form of a liquid and a vapor, etc. [79, 80]. This formed a basis for developing progressive and combined methods of hydro- and hydrothermal treatment of foodstuffs and other materials in IR-radiation: damping and heating of tobacco leaves prior to cutting; micronization; frying; drying and damping of grains; damping of cotton seeds; drying of fruits and vegetables; bread and pastry baking; drying, modification, and dextrinization of starch, etc.

The work [78] presents the ideas on system analysis and mathematical modeling of the processes of thermoradiant treatment of damp materials with infrared radiation, which enable one to substantiate not only the parameters of the optimal regime for the technological process but also to choose the most suitable method for controlling the processes under real operating conditions. Further advances in solving the topical problems of electrotechnology cybernetics using IR-radiation are to be expected in the coming years.

Clearly, it is difficult to give proper attention to all the numerous applications of results of the radiative transfer theory in one, though extensive, survey. And all of them are important, be it heat transfer by radiation in internal combustion engines or in radioelectronic equipment, thermoradiant drying of officinal plant raw material or investigating radiative-convective heat transfer in greenhouses.

However, one more extremely important aspect of the problem is noteworthy, i.e., the state of the art in investigating the optical properties of surfaces and media involved in heat transfer.

In [51, 81, 82] where works devoted to radiative characteristics of surfaces are discussed, results of investigations obtained before the eighties are predominantly reflected. More recent investigations of relatively pure materials, source ones for industrial systems, are given in [83]. In recent years data have been obtained on the indicated properties of ash and slags [84-88] and refractories [89-93]; their spectral emissivity, reflectivity and transmissivity, and scattering indicatrix in a wide spectral region have been investigated. The collected statistics permitted generalizations on the influence of the conditions of generation, composition, and structure of these materials on their radiative properties [86-88]. Thus, empirical dependences of the emissivities of ash and slag on their ferric oxide content in various modifications, ratios of the basic oxide constituents, and dimensions of microinhomogeneities were found. In [88] it is shown that this parameter plays one of the leading parts, and taking into account of it enables one to predict to acceptable accuracy the values of the radiative characteristics for the above materials.

Investigation of the analogous properties of disperse media in recent years has followed the path of improving calculation methods and collection of statistics on specific objects [84-102]. The works [94, 95] consider in detail the influence of temperature and particle size on the radiative properties of the medium. The dimensionless parameter $a = nS/\lambda$, where n is the refractive index, S is the particle diameter (μm), λ is the radiation wavelength, is introduced. The work [96] considers in detail mathematical models for calculating radiative properties and absorptivities of industrial gas media and gives generalizations for various spectra. A refined model for various concentrations of particles is given in [97]. Detailed data on the absorption coefficient and albedo of fly ash and coal are presented in [98]. It is shown that the parameters of scattering for the fly ash strongly depend on its refractive index for small particles, and weakly - for large ones. In [99] it is proved that deviation from the Bouguer-Beer law with increasing particle concentration and geometric thickness of the flow is a factor for many industrial units. The inequality of the chemical and disperse composition of dust particles yields a discrepancy to 50% in the absorptivity values. The works [100-102] are devoted to subsequent improvement of the calculation procedure for the radiative properties of pulverized coal flows. It is shown in them that contrary to previous concepts the absorptivity of the "average" particle decreases with temperature.

Most of the calculations of radiative transfer allowing for scattering are performed with the use of the properties of particles obtained according to the "turbid medium" theory. For real combustion products containing fly ash, etc., the particles are mainly spherical and have the outer surface approaching optically smooth since they have passed the phase transition. The relations between the particle size and the radiation wavelength also affect the method for calculating spectral effective cross sections: for small particles the calculation can be performed by simple Rayleigh formulas, for very large ones use can be made of geometrical optics, and for particles comparable with the wavelength solving the diffraction problem is needed [84, 102].

The basic initial data for the determination of the radiative properties of the unit volume of a light-scattering medium are local values of the function of particle size distribution, particle concentrations, radiative properties of the gas phase and of individual particles, temperature, and other parameters to an extent.

At the present time on the initial data (the size) of particles, to determine their radiative properties, numerous experimental investigations based on the application of various probes for sampling particles, on radiation of the characteristics of scattered light, etc. have been performed. Quite definite results are obtained on the particle microstructure, the particle size distribution function, and their concentration in different heat power plants [46, 51]. However, shortage of data on the scattering properties of gas-dust media presents serious problems in calculating heat transfer in units where pulverized fuels are burned. The work [62] gives an engineering method of calculating the scattering properties and emissivity of gas-dust media in the near infrared spectrum whose essence is as follows: based on the theory a table is drawn up of the coefficients of attenuation, scattering, and absorption and the mean cosine of the scattering indicatrix averaged over the wavelength range and over the particle fractions. The method enables one to simply and accurately take into account the polydisperse composition of the particles, the selectivity of their optical properties, and the presence of oxide films on the particle surface.

The gas phase of combustion products contains a great quantity of components; however, a major contribution to radiation is made by vibrational-rotational and pure rotational bands of molecules of H_2O, CO_2, CO, O, etc. Results of the calculations of radiative properties for these gaseous components are given in [46, 51, 103 and others].

Dealing with the issues of radiation selectivity, it should be noted that in practical calculations of heat transfer by radiation use is made of simplified methods in which either spectra of all bodies are considered continuous or, with a molecular spectrum of the medium, other bodies including suspended particles are considered as gray. In the second case the Hottel method of the weighted sum of gray gases is best known. S. P. Dedkov performed a series of investigations devoted to taking simultaneous account of the continuous and molecular spectra of bodies in calculations of heat transfer by radiation [96].

Thus, for calculations of radiative characteristics of surfaces and bodies only qualitative and semiquantitative calculation methods have been developed by now, which give no way of calculating these parameters to high accuracy in each specific case, resting on known data on the composition and structure of substances. Experiment remains the major tool for determining the radiative properties of heat transfer surfaces and media in high-temperature industrial units.

Analyzing the current state of the art and prospects for development of domestic methods of calculation and experimental investigations of radiative and combined heat transfer and comparing them with the world level one may draw the following conclusions: in recent years in industrially, scientifically, and technologically advanced countries the body of investigations of radiative heat transfer as applied to physicotechnical and applied engineering problems has noticeably grown; the specific weight of Soviet investigations of radiative heat transfer as compared to other modes of heat transfer was considerably lower by the late 80s than, for example, in the USA; despite the wide, on the whole, development of calculation methods, among the created mathematical models there prevail those for solving partial problems, and there are practically no multipurpose complexes of programs to solve the problems of combined heat transfer as applied to real conditions; the existing level of algorithms and software as applied to the problems of development of heat engineering devices, diagnostics, and identification of heat and mass transfer processes as a whole remains unsatisfactory; there is practically no exchange of software packages and individual modules, software products of the world market are insufficiently studied, and tooling and its metrological support remain the weakest point in organizing experimental scientific investigations of radiative heat transfer and optical properties of surfaces, media, and various materials as well as in performing measurements, control, regulation, and automation of technological processes.

Highlighting the need for efficient solution of the above problems, one should accept as promising the following trends in the development of investigations of radiative and combined heat transfer:

development of methods for calculating radiative and combined heat transfer allowing for the processes of combustion, medium motion, variability of its composition and temperature, and the influence of selectivity of the processes of scattering, absorption, and emission of radiation in the volume of the medium and on its boundaries;

developing and improving methodological support for heat engineering diagnostics of various technological devices (furnaces, combustion chambers, etc.) aimed at achieving their operating efficiency and reliability. Creation of calculation-experimental complexes and tooling for control and regulation of operating regimes in heat engineering plants in the process of their operation;

creation of efficient methods of radiative-conductive heat transfer in two-dimensional and three-dimensional selectively absorbing and emitting media with complicated boundary conditions taking into account phase transitions of the media, in particular, as applied to problems of producing high-value glass, growing crystals, and other technologies;

investigating radiative-conductive heat transfer in highly porous semitransparent, complex, and anisotropic materials, in particular, as applied to the problem of creation of highly efficient thermoprotective coatings;

improving promising methods to intensify industrial furnaces by using directed regimes of heat transfer, artificial regulation of the emissivity of the heat-absorbing surface, the masonry surface, muffles and radiation tubes, watercooled furnace elements, etc.;

generalization and unification as well as obtaining new data on the radiative properties of media and bodies (spectral and integral) for real operating conditions and new structural composite materials;

introducing into industry the results of investigations of radiative and combined heat transfer in various technical devices and technological processes, which contribute to their improvement and ensure reliability and efficiency of operation.

Reports and papers proposed in the program of the section "Radiative and Combined Heat Transfer" of the Minsk International Forum on Heat and Mass Transfer deepen the insight into the scale of the many-sided and extremely important scientific and technical problem of radiative heat transfer and give valuable information on the nuances of solving specific problems, many of which are briefly mentioned in this survey.

The present work has been made possible due to the participation of a team of noted scientists - specialists-heat physicists and heat engineers united by active work in the section "Heat Transfer by Radiation" of the State Committee for Science and Technology, which celebrated its 25th anniversary.

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